

FLEXIBLE CONDUCTOR CORE FOR SUPERCONDUCTING POWER CABLE AND  
MANUFACTURING PROCESS THEREOF

BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

The instant invention relates to electrical power conduction and specially to the manufacturing of a central core known as former, used in the manufacturing of superconducting cables, on the external surface area of said core several superconducting tapes are placed permitting a spiral conformation with a predetermined angle and lay.

DESCRIPTION OF THE PREVIOUS ART

The design of AC power cables with electric conductors that can contain superconducting compounds of metal oxides that have high transition temperatures ( $T_c$ ), preferably above  $77^\circ$  K and that can be cooled by liquid nitrogen under normal pressure is known. Said materials are called high temperature superconducting materials (HTS).

Some of the most commonly used HTS superconducting materials are the materials made of ceramic compounds or metal oxides such as Y- Ba- Cu-O, Bi- Sr- Ca- Cu-O or Pb-Sr-Ca-Cu-O in different compositions, all them with  $T_c$  above  $100^\circ$  K.

The superconducting tapes are made of ceramic elements that are fragile materials and  $T_c$  value drops when they are under stress or bent.

The high temperature superconductors can be important aspects

of technological advances and can be integrated as components of equipment or devices. An obvious application is the use of zero resistance properties, in superconducting state, to the passage of direct current and low power losses in the transmission of electric energy. In present transmission lines, electric energy is lost through heat when current passes through normal conductors. If electric energy is transmitted through superconducting cables, said losses can be eliminated with the subsequent savings in energy costs. This can be applied to any electric components having copper conductors, such as motors, transformers, generators and any equipment involved with electric energy.

Another practical application of these materials is in the field of electronics, taking advantage of the breaker effect of the Josephson junction, which can be used as an element in computers. The magnetic levitation phenomenon in superconductors can be exploited in transportation, for example in the case of the prototype of the train on superconducting rails developed in Japan. Moreover, an important application is in medicine, as diagnostic tool, where superconducting magnets are used in magnetic resonance equipment (MRI).

Tests conducted on low temperature superconducting cables have shown a lack of technical restrictions for the design of cryogenic cables, and bringing HTS superconducting materials

at operating temperatures is relatively simple using liquid nitrogen, which reduces the operating costs related to this type of cables.

Currently, HTS materials have some restrictions because of their critical characteristics ( $T_c$ ,  $H_c$ ,  $I_c$ ). Presently, researches have been focused on increasing the superconducting section to improve current conduction capacity, with a larger number of layers, from 4 to 6 in the case of Germany and the USA, 8 in Denmark, and up to 10 layers in Japan.

The direction of the sense of each tape layer alternates with each layer, with a diameter between conductors ranging from 3.0 cm to 4.0 cm. The superconducting tapes are applied with a lay length ( $L$ ) from 50 cm to 100 cm (Figure 4) in order to observe the behavior of the cable critical characteristics. In tests conducted on short segments of cables, independently of the design parameters (diameter and lay length), the current distribution between layers is relatively uniform, the superconducting section is used totally and the maximum values of critical current are obtained in the tests. In fact, values of 5800 A - 12000 A have been reached in short segments of cable.

Some US and Japanese companies have manufactured and tested superconducting cable models up to 500 cm long, obtaining current values not above 1700 A to 2000 A. Tests conducted on

500 cm segments have revealed problems of current distribution between layers because said distribution tends to be irregular due to electrodynamic problems related to the conductor per se. Particularly, the current conduction capacity of the core is determined by equidistant section of the current flow, because the time constant of the electromagnetic field diffusion in the axial direction tends to be much larger than the time constant of the electromagnetic field diffusion in the radial direction.

Moreover, in Patent WO 00/39813, a superconducting cable is described using high temperature superconducting materials HTS with a flexible core. This relates, however, to a traditional coaxial design with insulated HTS tape layers and in cold. Japanese Patent 06239937 A2 describes a superconducting cable with HTS materials and flexible core but involves a traditional design for DC (direct current) and insulation between each layer of HTS tape.

In US Patent 5,529,385 a superconducting cable similar to the object of the instant invention is described, but only with regard to the type of materials used. In US Patent 5,952,614 a superconducting cable similar with regard to the use of HTS materials and flexible core is described, but with a coaxial design, in cold, and traditional design of HTS tapes.

Although the inventions cited above coincide in some already mentioned aspects with the instant invention, they generally

focus on other construction characteristics, such as mechanical aspects, tape degradation and electric losses.

#### DESCRIPTION OF THE INVENTION

Hereinafter the invention will be described with reference to the drawings of Figures 1 to 4, wherein:

Figure 1 is a cross-sectional perspective view of a conductor core for superconducting power cable.

Figure 2 is a cross-sectional view of Figure 1.

Figure 3 is a perspective view of a tape-winding machine to manufacture the core of Figure 1.

Figure 4 is a side view of Figure 1 showing the length of the lay "L" on a segment of flexible conductor core.

Figure 5 is a more detailed perspective view of Figure 3.

Figure 6 is a perspective view of the header of Figure 5.

The superconducting core object of the instant invention is manufactured through the following steps:

- placing a corrugated support tubular element 11 (Figure 1) (known as "former") on a bed of rolls of a tape-winding machine;
- placing a stainless steel tape layer 12;
- coating with a copper tape layer 13;
- placing the superconducting element tapes 14, 15, 16, 17, 18 and 19 either in one sense or in the opposite sense and
- coating with a final unifying layer 20.

According to the manufacturing process of the superconducting

core, the tapes are submitted to a strain caused by the bends produced in the tape-winding machine and the central core when the layer is manufactured. This relative strain is determined through the following equation:

$$\varepsilon = \delta \sin \alpha D_f \quad (1)$$

where:

$\delta$  = thickness of the superconducting tape

$D_f$  = diameter of the central core (former)

$\alpha$  = placing angle of the tape on the central core.

Another type of strain appears when the cable is placed on storage reels or on a curved installation site. The strain occurring in this case is determined through the following equation:

$$\varepsilon = \pi \lambda \cos \alpha / p + p \sin \alpha / \pi D_b$$

where:

$p$  = lay length of the tape on the core

$D_b$  = bend diameter on a reel or duct.

From the abovementioned equations, it is obvious that a maximum angle (minimum lay length) is determined by the equation number 1 and a minimum angle (maximum lay length of the tapes on the cable core) is determined by equation number 2, being

$$\varepsilon = [\varepsilon] = 0.002 - 0.003.$$

Currently, it is difficult to obtain a uniform distribution of current between layers without developing special designs.

The analysis of traditionally shaped conductors having two, three or four superconducting tape layers shows that, in superconducting state, when the voltage drop throughout the conductor is not determined or measured, the current flows only in the first two external layers and is practically nil in the internal layers of the cable. The results show that the variation in the direction of the laying length has no important effect on current distribution.

To improve the abovementioned drawbacks, the applicant has developed a new design which consists of at least a cable with a central core (former) around which superconducting tapes are spirally placed, on at least two layers with a laying angle defined by the characteristic that some of the layers adjacent to the core are laid in a sense and the other external layers in the periphery of the core are laid in the opposite direction, in such a way that the laying lengths of all the other layers vary from a maximum  $P_{\max 1}$  and  $P_{\max 2}$  in the intermediate layers to a minimum  $P_{\min 1}$  and  $P_{\min 2}$  in the external layers, while the laying angle of the tapes in all the layers vary from  $\alpha_{\max 1}$  to  $\alpha_{\min 1}$  and from  $\alpha_{\max 2}$  to  $\alpha_{\min 2}$  at least in one of the layers of the tapes placed between the external surface of the core and the inferior part of the layer.

Where:

$P_{\min 1}$  and  $\alpha_{\max 1}$  = Minimum lay length and maximum laying angle of the tapes in the first layer of superconducting tapes, taking as reference the core axis.

$P_{\min 2}$  and  $\alpha_{\max 2}$  = Minimum lay length and maximum laying angle of the tapes in the first layer of superconducting tapes, taking as reference the core axis.

$P_{\max 1}$  and  $\alpha_{\min 1}$  = Maximum lay length and minimum laying angle in the last layers of superconducting tape of the section adjacent to the core having a given laying direction.

$P_{\max 2}$  and  $\alpha_{\min 2}$  = Maximum lay length and minimum laying angle of the tapes of the first layer of superconducting tapes of the second part of the layers having a sense opposite to the first part.

In this case, the superconducting core is designed to operate in alternate current, direct current and current pulses, using a layer of tapes made of low electric conductivity metals or alloys (Cu, Al, Ag). Said layers of superconducting tapes (one or more layers), and the laying direction of the tapes in the internal layers to the external layers changes only once independently of the number of layers. Thus, the number of times the layers of superconductor tapes change the



laying sense in the opposite direction presents a 1:1 to 1:2 ratio. It must also be taken into account that superconducting elements can be used in the layers in any shape, round, oval or in shape of a sector.

The conducting core of the superconducting cable 10 of Figures 1 and 2 is a cylinder-type conducting element consisting of several concentric sections longitudinally placed, having in its center a helical externally corrugated flexible tubular element 11 made of 304 or 316 stainless steel, which can have an external diameter ranging from 4 cm to 6 cm and an internal diameter ranging from 2 cm to 4 cm, with a corrugation depth varying from 0.5 cm to 1 cm. The corrugation pitch can be between 0.8 and 1.5 cm for a corrugation depth between 0.4 and 0.5 cm. In another embodiment, for depth between 0.4 and 0.6 cm, the corrugation pitch can be between 1.6 and 3 cm, above which a 304 or 316<sup>a</sup> stainless steel mesh is placed in order to offer a relatively flat surface for the next application. Said mesh consists of a first layer of stainless steel tapes 12, having a width between 4 and 5 cm and a thickness between 0.005 and 0.006 cm, a corrugated tube is placed with a spacing between 0.15 and 0.2 cm. Then one or two additional layers of stainless steel tapes are placed, from 2.5 to 4 cm wide and from 0.001 to 0.002 cm thick with a spacing between tapes ranging from 0.1 to 0.15 cm; then a first layer of Cu tapes, 13, is

placed, between 0.25 - 0.40 cm wide and 0.025 - 0.030 cm thick, which is applied with a laying length ranging from 2 cm to 100 cm depending on the cable design and the first layer of superconducting tape is to be applied with an application angle ranging from  $0^{\circ}$  to  $45^{\circ}$ , being the core characterized by the geometrical placing of a superconducting material which is a commercial product based on BISSCO tapes in the 22233 composition. Said tapes are between 0.38 and 0.42 cm wide and between 0.018 and 0.022 cm thick presenting a superconducting material section 0.018 thick and 0.35 cm wide, giving a current density of  $7 \text{ kA/cm}^2$  under the criteria of  $0.1 \text{ } \mu\text{V/cm}$ , with a superconducting material applied in three concentric layers 14, 15, and 16 of superconducting material tapes with a 2 cm to 300 cm long lay length, and with a  $0^{\circ}$  to  $45^{\circ}$  angle depending on the design required for each layer and with a direction that can be right or left. Then three other layers of superconducting material tapes 17, 18, and 19 are applied with a lay length ranging from 2 cm to 300 cm, with a  $0^{\circ}$  to  $45^{\circ}$  angle depending on the design of each layer and with a laying direction that can be right or left in the direction opposite to the layers previously placed 14, 15 and 16. Finally a reunifying tape made of an insulating material 20, commercial product that can be Mylar or Kapton, with a thickness ranging from 0.005 to 0.01 cm, and a width ranging from 2 to 4 cm. is applied.

According to figure 3 the manufacturing process of the superconducting core, Figure 1, 10 is conducted in a tape-winding machine designed for this purpose and consists of the following steps:

Placing the stainless steel corrugated central core (former) 11, on a bed of rolls 21, Figure 3, and then placing a layer of stainless steel tape to give uniformity to the surface 12, Figures 1 and 2; after coating, a layer of Cu tapes 13, Figure 1, is placed as initial layer. The tape-winding machine 23 is a table or bench structure placed longitudinally and presenting the following mechanical arrangements: an initial unwinding element 22 placed at the front end of the machine on which the core is placed for the application of the superconducting tapes, then an elongated bed of rolls 21 to avoid its flexion, then, a header element 24 projects adjacently and longitudinally, where the superconductor tapes are placed on reels 25, Figure 5, located at the sides of the header to accommodate the superconducting tapes individually. Having a diameter ranging from 20 and 25 cm, said reels supply the superconducting tape with a mechanical stress between 0.5 Kg and 6 Kg, without causing mechanical damage or losses of electric properties to the superconducting tapes. The number of reels can vary from 18 to 72, depending on the number of tapes to be used for the manufacturing of each layer of cable. The superconducting

tape passes through a second header 26 before being applied onto the cable core. Said header includes 18 to 72 guide elements 29, Figure 6, for the tape, depending on the number of tapes to be applied on the core and the application angle of the tapes can vary from  $0^{\circ}$  to  $45^{\circ}$  with a curve radius between 0 to 6 cm, depending on the angle and laying of the superconducting tape on the cable. With said machine it is possible to obtain laying angles from  $1^{\circ}$  to  $60^{\circ}$  with cabling lays from 2 cm to 300 cm. After this arrangement, a second bed of rolls 27, Figures 3 and 5, is placed longitudinally to support the superconducting core with the tapes and in the extreme part of the rear end there is a winding element 28 to receive the superconducting core with the tapes applied on it. After this initial layer, several superconducting material tapes are placed. Depending on the design and number of layers, said layers will be placed in one direction or in the opposite sense. Said procedure repeats itself as many times as the number of superconducting tape layers required by the design of the cable.

The following examples describe the results obtained and the comparative results in order to illustrate the invention without limiting its scope.

#### Example No. 1

A 1 m superconducting core segment was manufactured according to the characteristics shown on Table 1. This model of

superconducting core includes only 4 layers in order to test the theoretical models.

Table 1

	Layer number 1	Layer number 2	Layer number 3	Layer number 4
<b>Superconducting material</b>				
Tape thickness (cm)	0.022	0.028	0.028	0.022
Width (cm)	2.98	2.99	3.23	3.24
Crit. electric current (A) 1 $\mu\text{V}/\text{cm}$	42.2	39.6	40.5	39.3
<b>Space between tapes (cm)</b>				
	0.0057	0.0055	0.0044	0.0084
<b>Cable construction</b>				
Laying direction	Left	Left	Right	Right
Laying angle	25.54	13.24	11.08	35.8
Laying length (cm)	33.6	69.0	84.0	23.12
Number of tapes	46	50	49	6.40
Length of tape (cm)	2.55	2.58	2.61	2.65
<b>Current parameters</b>				
Relative current in each layer				
$i_1 = I_1/I_0$	10000	0.9981	0.9918	0.9467
Current density				

$$J_1 = I_1/I_0 \quad 0.2451 \quad 0.2669 \quad 0.2712 \quad 0.2167$$

It can be observed that the current parameters show that the percentage of tape utilization is within 99% ( $I_1/I_0$ ). This corresponds to a total current value in the cable  $I_0 = 4,500$  A, according to the current distribution in each layer.

#### Example No. 2

The traditional model was analyzed as is shown on Table No. 2 and the general parameters of the superconducting core were determined, using the superconducting materials as in example No. 1, in which the main characteristics of the superconducting core are:

Table 2

	Layer number 1	Layer number 2	Layer number 3	Layer number 4
<b>Cable construction</b>				
Laying direction	Left	Right	Left	Right
Layer radius (cm)	2.0	2.05	2.10	2.15
<b>Current parameters</b>				
Relative current in each layer				
$i_1 = I_1/I_0$	0.2000	-0.3007	0.5716	0.5282
Current density				
$J_1 = I_1/I_0$	0.4522	-0.5373	0.9971	1.0000
Maximum current				
$I_{\max} (A)$	1,373.3			

According to the previously mentioned parameters, a total maximum current of 1,373 A is obtained. From this it is obvious that for classical or traditional designs of superconductor core, for power cable application, alternating the laying direction in each layer does not result in a uniform current distribution ( $J_i$ ) in each layer. The major current circulation concentrates in the external layers of the cable, the internal layers working at a much lower capacity than the external layers.

The embodiments described above are not intended to be limiting to the scope of the claims and equivalents thereof.